Guidance on the Characterisation and Remediation of Radioactively Contaminated Land

ENVIRONMENT AGENCY

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Executive summary

This guidance is intended for Environment Agency (Agency) officers, and organisations involved in the characterisation and remediation of radioactively contaminated land, where the Agency will regulate the disposal of the wastes arising from remediation.

Guidance is given on the regulatory context for radioactively contaminated land; the interpretation of the Radioactive Substances Act 1993; and some of the relevant Exemption Orders issued under the Act.

The document also provides advice on:

- radiological protection criteria to be used in determining whether the levels of contamination left on site are acceptable;
- techniques for the characterisation and remediation of radioactively contaminated land;
- the selection of options for remediation.

The present guidance is intended for use under current legislation. It does not address possible requirements under the proposed regulatory regime for radioactively contaminated land, which is intended to mirror the Part IIA EPA 90 contaminated land regime.

Environment Agency

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Guidance on the Characterisation and Remediation of Radioactively Contaminated Land

1. INTRODUCTION

This document provides guidance and information for Environment Agency officers and other organisations on the characterisation and remediation of radioactively contaminated land.

Remediation of radioactively contaminated land takes place for various of reasons, but is frequently driven by plans to sell and change the use of land. Planning authorities are involved in such changes of use, and planning permissions to be issued. This involves the preparation of environmental impact assessments. When consulted, we advise planning authorities, developers and others on remediation standards and associated activities.

Remediation normally involves disposing of any radioactive waste arising, which will require prior authorisation by the Agency under the Radioactive Substances Act 1993.

This document provides:

- a description of the relevant **legislation** under which the Agency is the regulator, and guidance on the **interpretation** of this legislation;
- guidance on the **advice** regarding remediation targets to be given by the Agency when consulted by local planning authorities or other organisations;
- summary **information on techniques** for the characterisation and remediation of radioactively contaminated land.

The guidance is intended to ensure that all parties involved in the remediation of such sites are informed about the requirements of the regulatory system and of the recommendations from advisory bodies, such as the National Radiological Protection Board (NRPB). It provides information about the methodologies and techniques by which radioactively contaminated land can be characterised and managed; it also outlines good practice and thus should improve standards and consistency.

The SAFEGROUNDS Learning Network is a project managed by the Construction Industry Research and Information Association (CIRIA) on behalf of stakeholders concerned with the health, safety and environmental management of contaminated land on nuclear-licensed and defence sites. It is a useful source of information. Detailed guidance on the characterisation of contaminated or potentially contaminated land on nuclear-licensed and defence sites has recently been published [1]. This and additional information, including the regulatory framework for contaminated land on nuclear-licensed and defence sites, is provided on the SAFEGROUNDS website: www.safegrounds.com.

2. SCOPE

This guidance principally covers land in England and Wales that is radioactively contaminated due to previous practices involving man-made or natural radioactive materials.

It does not address radioactively contaminated land on nuclear licensed sites, which is regulated by the Health and Safety Executive (HSE) under the Nuclear Installations Act 1965. HSE's regulatory responsibilities also include establishing remediation criteria when sites are being delicensed. However, as the Agency is responsible for authorising radioactive waste disposals from nuclear licensed sites, parts of this guidance may be relevant for radioactively contaminated land on such sites.

Land belonging to the Ministry of Defence (MOD) is also subject to different regulatory requirements. For example, the Radioactive Substances Act (RSA 93) does not apply to operations carried out directly by the MOD. However, the declared policy of the Secretary of State for Defence is that where civil provisions do not apply, MOD standards should, as far as practicable, be “at least as good”. Many of the principles in this guidance will therefore be applicable.

The present guidance is intended for use under current legislation. It does not address possible requirements under the proposed regulatory regime for radioactively contaminated land, which is intended to complement the Part IIA EPA 90 contaminated land regime.

There should be close co-operation and liaison between all the interested parties during the investigation, characterisation, assessment and remediation processes. The relevant parties will include the site/liability owner, the site developer and remediation contractor, local planning authorities, local authority environmental health officers, Agency officers, HSE, local interest groups and non-governmental organisations (NGOs).

The document is structured as follows:

Section number	**Content**
3	Reviews where potential sources of radioactive contamination might arise.
4	Outlines the relevant regulatory requirements for dealing with radioactively contaminated land.
5	Presents the current guidance from the NRPB on the appropriate radiological criteria to be applied when considering whether remediation is required and when setting clean-up criteria.
6	Provides guidance on the factors to be considered in comparing remedial options and in selecting the most appropriate one.
7	Summarises the requirements for the assessment of potential radiological exposures arising from the site and for evaluating the impact of the remediation activity.
8	Outlines the procedures for investigation and characterisation of the site to provide input for both the dose assessment and for the selection and optimisation of the remediation strategy.
9	Outlines the generic requirements for planning and completion of the remediation work.
Annex 1	Summarises relevant potential remediation techniques

3. POTENTIAL SOURCES OF CONTAMINATION

Apart from the main nuclear power, research, production and fuel-cycle facilities and those regulated under the Radioactive Substances Act 1993, there is a wide range of sites in the UK where radioactive substances have been used and radioactive contamination of land may have occurred. The Department for Environment, Transport and the Regions (DETR) issued guidance on the types of processes that may have caused radioactive contamination [2]. These include sites where substances with elevated levels of naturally occurring radioactive materials were concentrated intentionally, or as by-products of other processes. These substances include:

- radium used for luminising;
- thorium and rare earths for alloying;
- catalysts (for example, some of those used at town gas manufacturing works);
- thorium-impregnated gas mantles;
- electron emitters in filaments in electronic valves;
- refractory bricks for high-temperature processing and the like;
- phosphates for acids;
- fertilisers;
- detergents;
- the smelting of some lead, bismuth, tin and zinc ores;
- the separation of produced water from oil and gas production;
- the descaling and disposal of affected equipment;
- uranium for glazing;
- heavy metal mining, for example, lead, tin and copper, (uranium was mined at a few sites in SW England);
- mineral sands processing;
- fuel and fly ash from coal-fired power stations.

In many cases the processing and contamination occurred before such materials were regulated as radioactive materials and the organisations responsible for the contamination have long since ceased to exist. In some cases the existence of the contamination has been known for a long time, but in others it has been rediscovered by potential developers or current owners. The major group of sites in this category are those where the contamination results from the use of or disposal of items (for example, in burning grounds) that include luminising materials. Current and past military sites are in this group, where the contamination has arisen from the disposal of old aircraft and vehicles with luminous instrument panels, or the operation of luminising workshops.

In addition, there are various other sites where contamination might have arisen as a result of medical applications of radium, and as a result of research using radionuclides (for example, universities, animal and plant research institutes). In other cases slightly radioactive materials have been used on account of other properties, such as high density (for example, e.g. depleted uranium in armour piercing shells on gunnery ranges).

Slags resulting from the smelting of certain ores will be contaminated. Some of these, particularly tin slags, have found widespread use in civil works because of their desirable structural properties. Contamination from the use of slags will be encountered in situations where there are no apparent links with the process that produced the contaminated material.

The nature of the industries and processes that may have resulted in radioactive contamination, means it is also likely that chemical contamination has occurred at these sites. Such non-radioactive contamination may be subject to regulation and control under the new contaminated land regime (see below).

4. REGULATORY SYSTEM

There is no statutory definition of radioactively contaminated land. Also, apart from the Nuclear Installations Act 1965, or under the planning regime, there is no legal regime under which characterisation and remediation can be compelled. Section 78YC of Part IIA of the Environment Protection Act 1990 (EPA 90), inserted by section 57 of the Environment Act 95, excludes radioactivity from the control regime for contaminated land established with the powers provided by Part IIA. Similarly section 78 of EPA 90 excludes radioactive waste from the meaning of controlled waste.

Where remediation and characterisation are undertaken, however, whether voluntarily or as part of the planning process, a number of legal provisions may be relevant. These are summarised in Table 1 below.

Table 1 Main legislation relevant to radioactively contaminated land

Legislation	Description
Radioactive Substances Act 1993 (RSA 93)	Legislation controlling the keeping and use of radioactive materials, and the accumulation and disposal of radioactive waste.
Exemption Orders made under RSA 93, including: • Substances of Low Activity, SI No. 1002, 1986 and amendment SI No. 647, 1992; • Phosphatic Substances, Rare Earths, etc. SI 2648, 1962	Statutory Instruments that exclude some materials, manufactured items, activities and premises from certain provisions of RSA 93.
Euratom Basic Safety Standards Directive 96/29, 13 May 1996	Basic radiological protection criteria and definitions accepted by the UK. A Direction has been issued to the Agency to ensure compliance with certain provisions of the Directive. However, most of its provisions are addressed in Ionising Radiation Regulation 1999 (see below).
Health and Safety at Work Act 1974	Legislation requiring employers to ensure safety at work for their employees.
Ionising Radiation Regulations 1999 (IRR99) SI 1999\3232	Principal legislation controlling work with radiation and radioactive materials. Relevant to characterisation, investigation and remediation activities.
The Radioactive Materials (Road Transport) (Great Britain) Regulations 1996 (due to be replaced late 2001) SI 1996\1350	Includes definitions of how materials (including waste) must be packed and labelled for transport, and what paperwork must accompany consignments.
Environmental Protection Act 1990, Part IIA (as inserted by Environment Act 1995, Section 57); Contaminated Land (England) Regulations 2000 SI 2000\227 & Contaminated Land (Wales) Regulations 2001 SI 2001\2197 (W.157)	Principal legislation relating to *non-radioactive contaminated land.*

4.1. Radioactive Substances Act 1993

The Radioactive Substances Act 1993, (RSA 93) is the principal legislation governing the keeping and use of radioactive materials (section 7), and the disposal and accumulation of radioactive waste (section 13 and 14). In England and Wales the Agency is the regulator under RSA 93 (although note that we do not regulate the keeping and use of radioactive material, or the accumulation of radioactive waste on nuclear licensed sites). The Scottish Environment Protection Agency (SEPA) exercises the corresponding role in Scotland.

RSA 93 specifies that a material is radioactive if it contains:

(a) an element specified in Schedule 1 of Section 1 of RSA 93, which is present at specific activity levels greater than those given in the adjoining columns of that schedule (Table 2, below). If this element is present at lower activity levels than those given in Schedule 1, then the substance is not classed as radioactive.

Table 2 Schedule 1 – The specified elements and their limiting specific activities

Element	**Bq/g**		
	Solid	**Liquid**	**Gas or vapour**
Actinium	0.37	7.4×10^{-2}	2.59×10^{-6}
Lead	0.74	3.70×10^{-3}	1.11×10^{-4}
Polonium	0.37	2.59×10^{-2}	2.22×10^{-4}
Protactinium	0.37	3.33×10^{-2}	1.11×10^{-6}
Radium	0.37	3.70×10^{-4}	3.70×10^{-5}
Radon	-	-	3.70×10^{-2}
Thorium	2.59	3.70×10^{-2}	2.22×10^{-5}
Uranium	11.1	0.74	7.40×10^{-5}

(b) any substances not naturally occurring, whose radioactivity is wholly or partly due to nuclear fission, neutron or ionising irradiation. Thus any substance containing man-made radionuclides will be classified as radioactive, irrespective of its specific activity, and will be subject to some or all of the provisions of RSA 93, depending upon whether one of the exemptions under the Act applies.

Section 2 of RSA 93 specifies that "radioactive waste" means waste which consists wholly or partly of:

(a) a substance or article which, if it were not waste, would be radioactive material;

(b) a substance or article which has been contaminated in the course of the production, keeping or use of radioactive material, or by contact with or proximity to other waste falling within paragraph (a) of section 2, or this paragraph.

Section 47 of RSA 93 defines “waste” and “disposal”

- “‘waste’ includes any substance which constitutes scrap material or an effluent or other unwanted surplus substance arising from the application of any process, and also includes any substance or article which requires to be disposed of as being broken, worn out, contaminated or otherwise spoilt”;

- "'disposal', in relation to waste, includes its removal, deposit, destruction, discharge (whether into water or into the air or into a sewer or drain or otherwise) or burial (whether underground or otherwise) and 'dispose of' shall be construed accordingly".

It is important to note that RSA 93 does not apply only at the point when radioactive material becomes radioactive waste. However, the Agency does not consider that radioactively contaminated land, *per se*, to be regulated under RSA 93 as either the "keeping" or "use" of radioactive material, or the "accumulation" or "disposal" of radioactive waste.

We do consider that, as soon as any action is taken in relation to that radioactively contaminated land, the potential for regulation under sections 7, 13 or 14 of RSA 93 arises. For example:

- the excavation of contaminated material and its disposal as low-level waste to Drigg clearly falls under the definitions in s.47 of RSA 93 for "waste" and "disposal" and would require prior authorisation for disposal under section 13 of RSA 93;

- prior authorisation would be required for the "disposal" by discharge to water of contaminated effluent resulting from an in-situ treatment, such as soil flushing.

The limits contained in RSA 93, or in Exemption Orders made under RSA 93, do not directly reflect the dose or risk criteria that may be required as a basis for deciding whether remediation is necessary and, if so, which remediation criteria are appropriate. This is an important point to bear in mind and has two important consequences.

On the one hand the preferred remediation option could be one where the doses or risks from the residual levels of radioactive material are acceptable for the envisaged use of the site. Further development of the site in future, however, could result in the production of radioactive waste requiring an authorisation for disposal.

On the other hand, it is possible for land to be contaminated with radionuclides at a level that would not bring waste produced from excavation under regulatory control, but which for some uses of the site might nonetheless result in doses or risks considered radiologically unacceptable.

Therefore radiological protection criteria need to be addressed in assessing remediation options. This is discussed further in Sections 5.5 and 6.

4.2. Exemptions from the provisions of RSA 93

A number of Exemption Orders have been made under the Act specifying the conditions under which materials or wastes defined as radioactive under RSA 93 are "exempt" from some or all of its provisions. Two key exemption orders are particularly relevant to radioactively contaminated land:

- Statutory Instrument 1986, No. 1002 and amended 1992, No. 647. The Radioactive Substances (Substances of Low Activity) Exemption Order (the SoLA Exemption Order);

- Statutory Instrument 1962, No. 2648. The Radioactive Substances (Phosphatic Substances, Rare Earths etc.) Exemption Order.

The SoLA Exemption Order specifies that solid radioactive waste is "exempt" from the provisions of section 13(1), (3) and (4) of RSA 93, provided that it is substantially insoluble in water and has an activity that does not exceed 0.4 Bq/g. Disposal of this waste does not require an authorisation from the Agency. The SoLA Exemption Order also applies to organic liquids and short-lived (less than 100s half-life) gases. This order is particularly relevant to wastes that contain any man-made radionuclides.

The Phosphatic Substances, etc, Exemption Order states that material that is radioactive solely because of the presence of one or more of the Schedule 1 elements (that is, actinium, lead, polonium, protactinium, radium, radon, thorium and uranium) and is substantially insoluble in water, is unconditionally exempted from the provisions of RSA 93 provided that the specific activity of ***each*** of the Schedule 1 elements present does not exceed 14.8 Bq/g (stated as $4x10^{-4}\mu Ci/g$ in the Exemption Order). This exemption includes waste disposal and is particularly relevant to wastes arising from operations involving naturally occurring radionuclides.

Changes to Schedule 1 of RSA 93 and the Exemption Orders were considered by DETR when the 1996 Euratom Basic Safety Standards Directive was implemented in the UK, but were not deemed necessary. A review of Exemption Orders (other than SoLA) is being undertaken by the Department for the Environment, Food and Rural Affairs (DEFRA) to see how they might be updated in the light of changes in circumstances since they came into force.

4.3. Interpretation of limits

A DETR report [3] has addressed the interpretation of RSA 93 and the SoLA Exemption Order. This is being considered for use in guidance to RSA 93 for non-nuclear users, which is being prepared by DEFRA, the Environment Agency, National Assembly for Wales, SEPA, Department of the Environment in Northern Ireland (DoE (NI)) and the Scottish Executive. The guidance given below has made some use of the DETR report. Some aspects of this guidance are summarised in Table 3.

Schedule 1 to RSA 93 – interpretation of limits

Many radionuclides in the actinium, uranium and thorium series occur both naturally and artificially. Schedule 1 applies to these radionuclides regardless of their origin. Thus the Schedule 1 limits are absolute values, inclusive of background levels. In most cases, this is of minor significance, as the background levels of uranium and thorium series radionuclides are typically ~0.03-0.05 Bq/g. However, there are some areas, such as the granitic rocks of South West England, where the activities of uranium and thorium series radionuclides are significantly higher (in the order of 0.15 Bq/g).

Phosphatic Substances, Rare Earths etc. Exemption Order – interpretation of limits

The Phosphatic Substances, Rare Earths etc. (PSRE) Exemption Order does not include guidance on the treatment of daughter products or background levels. This Exemption Order is interpreted by the Agency to mean that the activity concentration limits refer to the sum total of activity concentrations of all the radionuclides for each radioelement specified. It is also assumed, unless evidence is available to the contrary, that secular equilibrium has been established in the decay series.

The secular equilibrium assumption is particularly important in the case of Ra-226. When Ra-226 decays it produces three isotopes of polonium: Po-218, Po-214 and Po-210. This means that, when Ra-226 is in secular equilibrium with all its daughter products, for each Bq of Ra-226 present there are 3 Bq of Po. Accordingly, to ensure that the activity of Po in a material never exceeds the 14.8 Bq/g limit in the Exemption Order, it is necessary to ensure that the activity of Ra-226 does not exceed one-third of 14.8 Bq/g, that is to say 4.9 Bq/g. For this reason, the limit usually applied to Ra-226 in judging compliance of a material with the Exemption Order is 4.9 Bq/g. (Exceptions may be made for recently chemically separated Ra-226.) Similarly, the limit for Th-232 in judging compliance with the Exemption Order is 7.4 Bq/g, because its two daughter products, Ra-228 and Ra-224, will be present.

The PSRE Exemption Order limits are interpreted as including background levels, so they are absolute values.

Use of SoLA Exemption Order

The SoLA Exemption Order exempts substantially insoluble solids with an activity level less than 0.4 Bq/g. Its application falls into three broad categories:

- Where *natural radioelements that are not included in Schedule 1* (for example, potassium) are present in materials with a completely natural origin, they are not regulated under RSA 93. For example, a material containing only potassium-40 at naturally occurring concentrations would not be regulated; nor would materials containing tritium or carbon 14 at only natural concentrations. Where non-Schedule 1 radioelements are present in concentrations that have been enhanced by human activity, the materials are controlled under the Act in the same way as those containing artificial radionuclides, but with the naturally-occurring levels of the non-Schedule 1 radioelements discounted. To do this, it is first necessary to define the normal natural background concentration of the radionuclide in the relevant solid material. This then has to be subtracted from the measured concentration and the difference compared to the 0.4 Bq/g SoLA level. A simpler approach is possible when the natural background concentrations of the relevant radionuclides are much lower than the SoLA level; in such cases the SoLA 0.4 Bq/g level can be applied to the total measured concentrations of the relevant radionuclides in solid materials.

- For *artificial* radionuclides the SoLA Exemption Order level of 0.4 Bq/g is generally interpreted to be additional to the ubiquitous artificial background. This is acceptable to us This is important because, as a result of the atmospheric testing of nuclear weapons and the Chernobyl nuclear accident in particular, there are low, but measurable, levels of man-made radionuclides in the environment. Without this interpretation, all of the top surface of the Earth would be classified as radioactive.

- For *radioelements covered by Schedule 1* of RSA 93 that are in solid, substantially insoluble form, SoLA also applies. For example, a solid waste containing only radium-226 in substantially insoluble form would not need to be managed as radioactive waste unless the concentration of radium-226 was above 0.77 Bq/g (that is the 0.37 Bq/g from Schedule 1 plus the 0.4 Bq/g from SoLA).

The background concentration cannot be defined in a generic way because it varies from place to place. In general, users of SoLA need to agree the local background concentrations of the relevant radionuclides with their local Agency office. Some independent measurement of background concentrations in the locality is likely to be required.

Insolubility criterion in Exemption Orders

SoLA and the PSRE Exemption Orders are limited to solid radioactive waste that is "substantially insoluble". This term is not defined in the Exemption Orders. However, users of the Exemption Orders should recognise that they may be expected to demonstrate that the solubility of radioactive material is sufficiently small that the disposal impact will be dominated by the solid form, rather than from any material that may dissolve and migrate to, and via, groundwater. The Exemption Orders do not apply to the disposal of liquid wastes, although they may apply to suspensions of particulates.

Application of SoLA with PSRE Exemption Order

In appropriate circumstances, SoLA and the PSRE Exemption Orders may be used simultaneously. For example if a site had artificial radionuclides present that were less than 0.4 Bq/g above background (and hence SoLA was applicable), then any natural radionuclides also present could be categorised using the PSRE Exemption Order and disposed of according to its provisions.

Table 3

Summary of guidance on interpretation of limits for solid materials				
	Elements covered by Schedule 1 to RSA 93		**Elements not covered by Schedule 1 to RSA 93**	
	Schedule 1	**PSRE EO**	**Naturally occurring**	**Artificial radionuclides**
Background levels deducted?	No – limits are absolute values	No – limits are absolute values	Yes – only enhanced levels regulated	Yes – ubiquitous background (weapons testing fallout and the like) deducted
Qualifications for physical and chemical properties	None	Substantially insoluble	If SoLA EO applied: substantially insoluble	If SoLA EO applied: substantially insoluble

4.4. Comparison with limiting values

The following approach is recommended to compare sample measurements with the limiting values in the appropriate Exemption Orders and RSA 93.

- Determine radionuclide activity concentrations in appropriate numbers of representative samples (see Section 7).
- Determine background levels for radionuclides at/adjacent to the site using similar methodologies for sample collection and preparation (for example, obtain similar levels of particle size and organic matter content). If the site has been substantially altered by the construction of buildings, roads and/or drains, then comparison with background levels in undisturbed areas adjacent to the site might be more relevant. Take care to avoid sampling in areas with elevated contamination levels because of local sources, for example, plume wash-out.
- Derive mean (or other relevant statistical parameter, agreed on a site-by-site basis) background levels.

If artificial radionuclides are present then, if the specific activity of the representative contaminated land sample minus the mean background specific activity is less than 0.4 Bq/g, the material is treated no differently from non-radioactive material. It can then be disposed of in accordance with its other properties.

If only naturally occurring radioelements as specified in Schedule 1 of RSA 93 are present then, if the specific activity of the representative contaminated land sample (including the mean background specific activity) is less than the Schedule 1 limits for each radioelement specified, the material is not considered to be radioactive. It can then be disposed of in accordance with its other properties. If the specific activity of the representative contaminated land sample is above the Schedule 1 limits but less than 14.8 Bq/g (or 4.9 Bq/g for Radium), then the material, although radioactive, is exempt from RSA 93. It can then be disposed of as exempt waste and in accordance with its other properties.

For natural radioelements not specified in Schedule 1 (such as C-14 and H-3), the position is the same as for artificial radionuclides. That is, determine the natural background of these radionuclides at or adjacent to the site, subtract these from the specific activity of a representative sample of the material and compare to the SoLA limit of 0.4 Bq/g.

Secular equilibrium should be assumed to be present unless there is a basis to assume otherwise, such as analytical measurements, knowledge of the source and/or previous processing of the material. Each of the radioelements (measured or assumed) should be assessed against its own limits (Schedule 1 of RSA 93 or the PSRE Exemption Order) and if any exceeds its limit, then the material is radioactive and/or not exempted.

4.5. Averaging volume

Another difficulty in ascertaining compliance with limits on waste materials for disposal is the matter of the volume or mass over which it is reasonable to consider the average activity concentration.

In correctly sentencing waste materials, a critical consideration is the representative activity concentration for a given volume of waste. This is referred to as the averaging volume and is not defined in any UK legislation or regulatory guidance. Since radioactive contamination is often heterogeneous in nature (containing, for example, distributed discrete point sources), the remediation proponent is faced with an important decision on what represents an acceptable averaging volume.

This decision needs to be considered on a case-by-case basis and agreed with the regulator. It will be influenced by:

- the properties of the contaminating radionuclides;
- the feasibility and cost of monitoring and segregation;
- the means by which the contamination occurred and the nature of the contamination – this may influence the distribution of radionuclides and the potential for "hot spots";
- the availability of appropriate disposal routes for particular waste streams;
- the risks to remediation workers handling the materials;
- the relationship with radiological assessments made – these may not hold if averaging procedures are liberal (such procedures may lead, for example, to "hot spots" being left on a remediated site, even though surface material has a low average specific activity).

In practice, averaging volumes established in the UK have typically varied between 0.1 m^3 and 10 m^3.

Averaging aims to give a representative measurement of bulk activity. The approach to averaging should involve making sensible decisions on averaging volumes that allow sentencing to be carried out in a cost-effective manner without unacceptable risks to the public. The objective of averaging should not be the dilution of activity. In particular, it is unacceptable to mix large volumes of uncontaminated material with active material to try to reduce the category of waste (for example, to allow what was intermediate-level waste (ILW) to be disposed of to Drigg as low-level waste (LLW)).

4.6. Waste categories

Interpretation of the limits to be applied for the various categories of solid wastes, which contain radionuclides in concentrations above those occurring in the natural background, are summarised in the following table.

Table 4 Specific activity limits to be applied in determining categories of solid wastes containing 'Above Background Levels' of radionuclides

	Waste characteristics	Specific activity, Bq/g	Waste category
1.	Wastes containing man-made radionuclides	≤ 0.4	Exempt
		> 0.4	Low Level Waste (LLW)
2.	Wastes containing Schedule 1 elements only	≤ (Schedule 1, Column 2 limit for each element)	Outside the scope of RSA 93
	Wastes containing Schedule 1 elements only	> (Schedule 1, Column 2 limits) and ≤ 14.8	Exempt
	Wastes containing Schedule 1 elements only	> 14.8	LLW
3.	Wastes containing mixtures of man-made radionuclides and Schedule 1 elements	≤ 0.4 (***excluding*** contributions from all Schedule 1 elements and their daughters, ***provided*** none exceed their Schedule 1 Column 2 limits)	Exempt
		> 0.4 (***excluding*** contributions from all Schedule 1 elements, which do not exceed their Schedule 1 Column 2 limits, and their daughters)	LLW
4.		> 4 GBq/te alpha > 12 GBq/te beta/gamma	Intermediate Level Waste (ILW)

Note: In interpreting the PSRE Exemption Order, the limit for Schedule 1 elements (14.8Bq/g) needs to be reduced for Ra-226 and Th-232 where polonium daughters are present (see Section 4.3).

4.7. Part IIA of the Environmental Protection Act 1990

Part IIA of the EPA 90, which came into force in England on 1 April 2000, introduced a regulatory regime for the identification and remediation of contaminated land. By virtue of section 78YC, Part IIA of the EPA 90 does not apply to harm or pollution of controlled waters, so far as it is attributable to any radioactivity possessed by any substance, except as provided in Regulations. No such Regulations have yet been made. Where a radioactive substance has other properties, such as toxicity, Part IIA will apply in relation to those properties.

The legislation is supported by the DETR Circular 02/2000 [4], which includes a statement of government policy, a description of the regime, the statutory guidance and an explanation of the supporting Regulations. The Contaminated Land (England) Regulations 2000 [5] deal with particular aspects of the regime, such as "Special Sites", public registers and remediation notices.

The principal regulators for Part IIA are local authorities, which are responsible for identifying contaminated land. This regime provides a statutory definition of “contaminated land” that is based on risks of significant harm to human health and the environment or pollution of controlled waters. Land can be determined by a local authority as contaminated where inspection has identified substances in, on or under the land and where it has established that they are causing, or could cause, significant harm via identified pathways to identified “receptors”, or that they are likely to, or are causing, pollution of controlled waters.

The Agency has an important complementary regulatory role with specific responsibilities:

- to provide relevant information held by us to local authorities;
- to be the enforcing authority for any land identified as a “Special Site”;
- prepare a national report on the state of contaminated land;
- provide advice to local authorities on identifying and dealing with pollution of controlled waters and remediation.

By adopting the principles of risk assessment and risk management, we intend to ensure that contaminated land is managed effectively, based on its current use and environmental setting.

4.8. Regulations relating to the movement of radioactive material

Regulations for the transport of radioactive materials are produced by the International Atomic Energy Agency (IAEA). The most recent version is TS-R-1 *Regulations for the Safe Transport of Radioactive Material - 1996 Edition*. International Atomic Energy Agency, Safety Series No. TS-R-1, issued in 1996 [6].

For road transport, IAEA regulations are implemented in the UK by the Radioactive Materials (Road Transport) (Great Britain) Regulations 1996 *The Radioactive Materials (Road Transport) (Great Britain) Regulations 1996, Statutory Instrument 1996* No 1350 [7]. The regulatory authority for these regulations is the department for transport, local government and the regions (specifically the Radioactive Materials Transport Division). The regulations include requirements as to how materials (including waste) must be packed and labelled for transport and which paperwork must accompany consignments. Radioactive materials are defined as those where the specific activity exceeds 70 Bq g^{-1} (head of chain plus daughters in secular equilibrium). If the specific activity is below this threshold, the regulations do not apply to the consignment.

New transport regulations are expected later in 2001 to implement TS-R-1. The Ionising Radiations Regulations 1999 (IRR99) also describe requirements for the movement of radioactive materials where the transport regulations do not apply. The specific requirements of the regulations should be satisfied for all movements of radioactive material.

In the case of LLW consignments to Drigg, it should be noted that British Nuclear Fuels Limited (BNFL) places constraints on the nature and packaging of materials to be disposed of in addition to those included in the transport regulations.

5. RADIOLOGICAL PROTECTION PRINCIPLES

Before investigating and considering remediation options, it is important to understand the relevant radiological protection principles. The previous section sets out the regulatory system for radioactive waste accumulation and disposal and the waste categories that system establishes.

This section describes the radiological protection principles and criteria in the context of the remediation of radioactively contaminated land and is based on guidance from (NRPB) [8].

5.1. Conceptual framework

The conceptual framework of radiological protection recommended by the International Commission for Radiological Protection (ICRP) [9], which is endorsed by the NRPB [10, 11], recognises two types of situation:

- a “practice” involves the use of a radioactive source or a situation involving a source to achieve some purpose – it adds radiation exposures;
- an “intervention” is designed to redress a situation where there is real or potential radiation exposure from a post-situation or practice – it reduces radiation exposures.

Practices and intervention require different approaches to radiological protection. The system of radiological protection recommended by ICRP is as follows.

Practices:

1. No practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or society to offset the radiation detriment it causes (justification of a practice).
2. In relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received should be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account. This procedure should be constrained by restrictions on the doses to individuals (dose constraints), or the risks to individuals in the case of potential exposures (risk constraints), so as to limit the inequity likely to result from the inherent economic and social judgements (optimisation of protection).
3. The exposure of individuals resulting from the combination of all relevant practices should be subject to dose limits, or to some control of risk in the case of potential exposures. These limits to ensure that no individual is exposed to radiation risks that are judged to be unacceptable from these practices in any normal circumstances (individual dose and risk limits).

Intervention:

1. The proposed intervention should do more good than harm. That is to say the reduction in detriment resulting from the reduction in dose should be sufficient to justify the harm and the costs, including social costs, of the intervention (justification of intervention).
2. The form, scale and duration of the intervention should be optimised so that the net benefit of the reduction in dose - that is, the benefit of the reduction in radiation detriment, less the detriment associated with the intervention, should be maximised (optimisation of intervention).

The distinction between practices and intervention may not always be clear in the context of land contaminated with radioactivity.

However, two main categories of situations can be identified, as follows.

- A change of land use is proposed that is expected to increase public access and exposure. The system of control for practices should be applied, even though the practice that led to the contamination is no longer taking place.
- Contamination is discovered on land to which the public has access, but for which no change of use is proposed. This situation should be considered as an intervention.

Where a radioactively contaminated land situation does not fall clearly into either the practice or intervention category, it should be handled in terms of the principles and criteria for practices unless there are clear reasons to suppose that this could do more harm than good.

5.2. Need for a dose assessment

To apply these radiological protection principles to radioactive contaminated land, an assessment of the potential radiological exposures is required. Section 6 gives guidance on the scope and nature of an appropriate methodology for the radiological dose assessment required. The risks of serious health effects being incurred can be calculated from the effective doses or committed effective doses estimated in an assessment by multiplying those doses by the factor 0.06 Sv^{-1} [12]. This is the dose-risk factor adopted by ICRP in Publication 60 [9] for assessing the frequency of induction of fatal cancer and serious hereditary effects in a general population of all ages.

5.3. Practice situations

A constraint applies to the remediation strategy optimisation process. To ensure that doses and risks to the public will not be unacceptable, the risk to a representative member of the critical group (see Section 7.2) attributable to the residual contamination should not exceed a maximum risk of 10^{-5} y^{-1}. For year-on-year exposures over a lifetime, this corresponds to the risk associated with an effective dose rate of about 0.3 mSv y^{-1}.

Some remediation options will result in a dose to the critical group of significantly less than 0.3 mSv y^{-1}. The site owner or developer should consider these in the assessment of alternative options. In some cases it will be appropriate to select such an option.

It is unlikely that significant expenditure to reduce excess risk to an average member of the critical group for future site occupants below about 10^{-6} y^{-1} would be warranted on radiological protection grounds. This corresponds to an annual dose below about 20 μSv. There may be simple and inexpensive measures that could further reduce risk below 10^{-6} y^{-1} and these should be taken, but a detailed analysis of options is not needed.

5.4. Intervention situations

Most instances in which the Agency is involved with radioactively contaminated land will be through the development of land; that is, they will probably be considered as practices. The description below of intervention is largely taken from NRPB guidance [8] and is included for completeness.

The NRPB has recommended that if projected lifetime dose to the critical group (including past doses) is estimated to exceed 1 Sv, then the implementation of measures to reduce this will almost certainly be justified. Depending on circumstances, it may be justified to implement protective actions where projected lifetime doses are below 1 Sv, but each situation needs to be considered on a case-by-case basis.

Where options exist for reducing future exposure without involving major resources or disruption, then these should probably form part of the overall intervention strategy. In contrast, the implementation of measures that involve major resources or disruption should be matched by a corresponding reduction in future exposures. It is unlikely that options involving major resources or disruption would be appropriate unless they were expected to avert doses of at least several millisieverts in a year.

Annual dose limits for members of the public do not apply directly to intervention situations because they could require actions that might do more harm than good. However, the aim of seeking to limit inequity between individuals applies in all cases, and therefore could in some circumstances (subject to satisfying the justification requirement) imply the use in intervention situations of criteria similar to those applied to practices.

Dose criteria represent the balance between the harm and benefit of an activity, and do not represent a boundary between safe and unsafe. The harm and good associated with intervention, and hence the dose and risk criteria, can be at very different levels to those for practices.

5.5. Optimisation

Optimisation involves comparing of remediation options on the basis of their expected radiological impacts on the public and workers, their financial costs and other factors.

The radiological protection criteria set constraints on the options to be included in the comparison. In particular, for practice situations no option should be included if it entails a risk from residual radioactive contamination above 10^{-5} per year, equivalent to a dose of about 0.3 mSv per year.

One option for remediation is to excavate and dispose of contaminated material from the site so that all residual material is at or below an appropriate activity limit (for example Schedule 1 of RSA 93, or relevant Exemption Order). This offers the advantage that, unless there is a future tightening of regulations, regulatory controls will not apply to the disposal of any radioactive waste that may be produced from the site in future. However, taking this approach alone in determining remediation end points has the disadvantage that it does not ultimately ensure that a specified residual risk can be achieved. This would depend on the radionuclides, their distribution and the precise nature of use of the land.

The preferred approach to optimisation is to consider the doses or risks from any residual radioactive contamination, along with other factors. All the factors relevant to optimisation should be included in a more broadly based comparison of options, rather than carrying out a separate comparison of options for the purposes of optimisation of radiological protection.

The selection of remediation options is discussed in Section 6.

6. SELECTING THE REMEDIATION OPTION

6.1. Option studies

This section considers how options can be compared in order to select the best practicable option for remediation of the site. Any comparison of options should include factors such as radiological and non-radiological environmental impacts. The scale and complexity of the comparison will depend on the nature and scale of the contamination.

Formal “best practicable environmental option” (BPEO) studies can be conducted. The BPEO was defined by the Royal Commission on Environmental Pollution in 1988 [13] as “the option that provides the most benefits or least damage to the environment as a whole, at acceptable cost, in the long term as well as in the short term”. The BPEO is intended to be the outcome of a systematic consultative and decision-making procedure, which emphasises the protection and conservation of the environment across land, air and water. Options are assessed against criteria such as environmental effects, potential radiation dose to members of the public, regulatory restrictions, technical feasibility and cost.

BPEO studies normally involve obtaining quantitative and qualitative information on the generated options, initial screening of options on the basis of operational and regulatory constraints, and a final analysis of the favoured options using a pragmatic application of decision-support techniques.

In general, the development and selection of the remediation option will need to take account of:

- environmental impacts;
- doses to workers and members of the public during the remediation process;
- cost of implementation (site infrastructure arrangements/constraints, waste storage and disposal);
- technical feasibility/developmental status of techniques;
- timescales for completion;
- demonstration of success;
- monitoring (short and long term);
- opinions of the public and other stakeholders;
- enhanced value of site.

These are discussed briefly below.

Environmental impacts (after remediation)
The environmental impacts of a contaminated site after remediation and for the proposed use are an important factor, in particular the doses due to residual radioactive contamination. The radiological protection criteria in Section 5 set constraints on options to be included in the comparison. Remediation standards for a specific site follow from the remediation option selected. The standard to be achieved, in terms of residual risk or dose, or the residual contamination level (Bq/g) is what the selected option is capable of achieving.

Doses to workers and members of the public during the remediation process
The doses to workers and members of the public during the remediation process should be minimised through the use of appropriate protective equipment and the design of the remediation plan, use of containment, dust suppression and the like. Some techniques may be inherently safer than others in this respect.

Cost of implementation
One of the factors determining the type of remediation to be used will be the cost associated with it. The cost of remediation should be commensurate with the added level of protection to the public afforded by its implementation. The costs need to address the impact on the site infrastructure and potential requirements for waste storage and disposal.

Technical feasibility/developmental status of techniques
Many of the remediation techniques (described in Annex 1) have not yet been applied for radioactive contamination on a large scale or in field situations. The effectiveness of any technique will need to have been adequately demonstrated before it is considered as a serious option. It may be expedient in some cases to use the sites for testing new technologies, but this is unlikely to be a common practice.

Timescales for completion
The remediation of radioactive contaminated land is likely to be part of a general re-development package for an area. There may therefore be a finite timescale in which the remediation has to be completed for other objectives to be met. This would imply that proven techniques would have the advantage, even if these were more expensive.

Demonstration of success
One of the major requirements of the remediation technique will be the demonstration that contamination has been removed and/or reduced to the agreed levels. The cost of this exercise also needs to be considered in the overall option selection. A non-intrusive in-situ technique, for example electro-remediation, may require a comprehensive characterisation programme to demonstrate its effectiveness.

Monitoring (short- and long-term)
A degree of environmental monitoring during the remediation exercise is expected to demonstrate that the environmental impact being controlled was acceptable. Some techniques have different requirements for air or surface/groundwater sampling.

Long-term monitoring may be required for in-situ treatments. For example, the integrity of stabilised or solidified products will change over time, causing the leach rates of contaminants to increase. If the remediation if effective, and demonstrated, then the requirement for long-term monitoring should be limited.

Opinions of the public and other stakeholders
In developing options, the site owner should consider the views of a broad range of stakeholders. The degree of involvement with stakeholders will depend on, amongst other things, the extent of contamination. However, public acceptability of any option will also be concerned with wider issues such as the number of lorries in the vicinity, noise, dirt and the like. Stakeholder involvement may take the form of informing and consulting on the extent of contamination and the options for remediation available. Planning permissions and permit applications are often important mechanisms for stakeholder involvement.

Enhanced value of site
The level of remediation undertaken will influence the future use of the site. It may therefore be more cost-effective to remediate to a degree allowing full and unrestricted use of the site in the long- term if, by doing so, the value of the land increases.

7. DOSE ASSESSMENTS

This section addresses the assessment or estimation of doses resulting from the presence of radioactively contaminated land and the impact of the proposed remediation strategy(ies) on these doses. The objective of the dose assessment is to assist in the selection of the optimal remediation strategy and to ensure that the remedial end-points are consistent with the radiological protection criteria.

It is proposed that in considering proposals for the remediation of contaminated sites, the site owner or developer should provide dose assessments.

7.1 Nature and scope of assessment required

The dose assessment needs to be sufficient for influencing decisions on the optimal remediation strategy, if any, and to define acceptable remediation criteria for radioactive substances.

The assessment methodology should be as simple as possible and transparent. The assessment needs to be understood by a range of people with different levels of expertise in radiological assessment, such as regulators, operators, independent assessors and other interested parties.

The assessment methodology and data should be reasonable and robust. They should provide, as far as is possible, a realistic indication of exposures, or, if necessary, a cautious indication. The choice of methodology or data should not be overly cautious, however. This might lead to, for example, a poor comparison of different remediation strategies, or remediation costs that far outweighed the radiological protection benefits obtained.

An assessment is often a multi-stage analysis that will be used as a management tool for the remediation process. An assessment needs to be made of the site as it is initially. This will identify key sources and pathways (see section 7.2) that dominate the radiological impact. Knowledge of these sources and pathways will guide the choice of remediation options, each of which can be prospectively assessed. Interim assessments may be required as remediation work progresses, to monitor how effectively radiological protection objectives are being achieved, and to modify the remediation strategy as required if further data become available. An assessment of the remediated site may also be appropriate to determine its acceptability for development and use.

A full range of remediation options should normally be addressed in the dose assessment, from the option of taking no remedial action to a complete decontamination of the site (see Section 6). It may be appropriate to include the isolation or immobilisation of activity on the site.

An approach in which a range of different strategies are addressed in a scoping assessment may be appropriate. A smaller number of strategies or a single strategy would then be considered more fully. Detailed assessment of one proposed strategy might be necessary to indicate the quantity of material and activity that would need to be removed.

The assessment should address the impact of the works necessary to remediate the site, including the impact on the workers carrying out the remediation, as well as the impact from any other work being undertaken to change the use of the site and from its planned future use.

The assessments normally relate to the “next planned use” of the site. However, in setting out the options for remediation, it may be appropriate to also consider remediation for “any use” of the site. This may represent a more onerous remediation in a case where, for example, the next “planned use” is for light industrial purposes. However, remediation for “any use” may be a preferred option.

7.2. Assessment methodology and data

The concept of “pollutant linkage” from a source, via a pathway, to a receptor has already been referred to in Section 4 in the context of *non-radioactive contaminated land*. For dose assessments, an equivalent approach is taken. There can be a radiological impact from the contamination only if there is a source (radioactively contaminated land) and also one or more pathways and receptors. For a given source, an “exposed group” is any group of members of the public within which exposure to radiation is reasonably homogeneous. The exposed group receiving the highest dose from a given source is the “critical group”. The receptor will be a representative member of the critical group.

A range of potential pathways for human exposure generally needs to be considered. The following pathways should be considered:

- external exposure;
- inhalation of dust.

The following are examples of pathways that may also need to be considered, depending on the situation:

- inhalation of radioactive gases;
- ingestion of soil and dust;
- ingestion of agricultural products;
- ingestion of food grown in gardens and allotments;
- ingestion of soil attached to root vegetables;
- ingestion of wild foods;
- ingestion of drinking water;
- dermal contact.

Pathways can be very complicated in reality. Examples of effects that may need to be considered for specific pathways include: potential for external exposure indoors as well as outdoors; dust sticking to the skin or being carried indoors on shoes; consumption of products (meat and milk) from animals eating forage grown on contaminated land, as well as from animals grazing directly on contaminated land; use of contaminated water for irrigation; and dispersal of contamination by animals, for example, burrowing animals. The detail with which pathways need to be analysed is case-dependent.

It may be necessary to consider the impact of radioactive decay and ingrowth of daughter radionuclides, depending on the particular radionuclides contaminating the site. A potentially important example is the decay of Ra-226 to Rn-222 and its progeny, which would lead to the need to consider the pathway of inhalation of radioactive gas.

The above list of pathways may not be complete; in each assessment all significant pathways should be identified as part of the assessment process. For example, in some situations, uptake of tritium through the skin may have to be addressed.

The US National Council on Radiation Protection and Measurements (NCRP) Report No. 129 [14] is an important source of information. It describes mathematical equations or models for calculating doses from different pathways and gives appropriate values for parameters of the models, or data that can be used to calculate parameter values.

The following equation is provided as an example of the type of model used to calculate doses. An equation that can be used to calculate committed effective dose for inhalation outdoors for a radionuclide, E_{inh} (Sv y^{-1}), is:

$$E_{inh} = Df_{inh} \times C_{air} \times R_{out} \times T_{out}$$

where Df_{inh} is the inhalation dose factor (Sv Bq^{-1});

C_{air} is the average outdoor air activity concentration (Bq m^{-3});

R_{out} is the average breathing rate outdoors (m^3 d^{-1}); and

T_{out} is the days per year spent outdoors on contaminated land.

Ways of estimating the four parameters in the expression used to calculate E_{inh} and appropriate data are discussed in NCRP Report No. 129.

The assessment should be based on source data obtained from the site characterisation. In the above example of inhalation of dust, the activity concentration in the dust material, used to estimate C_{air}, would be based on data from the site characterisation. It may also be appropriate to take account of the fact that the activity distribution is not homogenous (exposure may not be continuous).

The critical group is defined over all pathways of exposure. In many cases, a single pathway will dominate and the critical group appropriate to that pathway will be clear, but in some cases the critical group may need to be justified by a more detailed analysis. In the above example of inhalation of dust, if the remediated land was to be used for recreation, the critical group might be dog walkers; if the remediated land was to be used for housing, the critical group might be children playing in gardens.

Only typical behaviour of a member of the critical group needs to be considered; exotic or pathological behaviour can be excluded. By definition, however, the habits and behaviour of the representative member of a critical group will be selected to give a cautious estimate of exposure.

It is often useful to present the results of dose assessments in the context of exposures to background radiation levels; however, compliance will be with dose limits or constraints that relate to the additional exposure due to contamination. These dose limits and constraints have values that are typically less than exposure due to natural background radiation.

Important assumptions on which the assessment is based should be made clear. This includes assumptions made about controls on activities during future use of the land.

8. SITE CHARACTERISATION

This section presents an overview of site characterisation on radioactively contaminated sites. A more detailed description of site characterisation on nuclear-licensed sites and defence sites is given in [1].

The characterisation of a potentially radioactively contaminated site is carried out using most of the techniques and health, safety and environment considerations relevant to the characterisation of a chemically contaminated site. The principal differences in the methods used relate to three factors:

- radioactivity presents different hazards from chemical contaminants;
- radioactivity is (in many circumstances) easier to detect on site than most chemical contaminants;

- radionuclides decay and ingrow. The radionuclide fingerprint will change with time. Short-lived radionuclides will have decayed; in other cases, daughter radionuclides will ingrow and add to radioactivity concentrations.

The characterisation of a contaminated site generally consists of the following:

Phase of investigation	**Objectives**	**Typical activities**
Preliminary investigation	Preliminary conceptual model	Desk study Site reconnaissance (visual inspection)
Exploratory investigation	Revised conceptual model	Design of the site characterisation programme Production of documentation, such as: • method statements; • health, safety and environment plan; • quality programme; Site investigation, potentially including: • soil gas survey; • radiological survey(s) (ground and groundwater); • geophysical survey; • intrusive investigations (construction, logging and sampling from trial pits and boreholes). Installation of permanent monitoring points Laboratory analysis of samples Interpretation of data Reporting

Existing guidance documents [15, 16, 17, 18] give details of the procedures that should be adopted for characterisation of chemically contaminated sites.

The information given in these documents is not repeated here. Instead, an overview of the issues relating to the characterisation of potentially radioactively contaminated land is presented.

8.1. Objectives

There are a number of possible objectives of a site characterisation programme. For example, a site characterisation may:

- determine if a site is contaminated;
- determine whether the contamination is causing, or is unlikely to cause, contamination of neighbouring properties;
- evaluate contaminated land liabilities;
- provide data for input to a health and/or environmental risk assessment;
- provide data for planning the remediation strategy;
- identify legal requirements to be met;
- aid in the categorisation of wastes (for example, are materials LLW or exempt wastes).

In many cases, it will be appropriate to evaluate both chemical and radioactive contamination during a single site characterisation programme.

8.2. The desk study/ preliminary conceptual model

The desk study of a potentially radioactively contaminated site is undertaken in the same manner as for a potentially chemically contaminated site. All information relevant to actual or potential contaminant sources, migration pathways and receptors should be collated and evaluated. For example, the following information may be compiled:

- history of the site (identification of potentially contaminative activities and potential contaminants associated with these);
- maps/plans and photographic records;
- previous site characterisation data (geological, hydrogeological, contaminants);
- routine on-site and off-site monitoring reports;
- incident and accident reports;
- waste management and disposal practices/records.

The conceptual model of a site is developed from an interpretation of the data. The Agency has produced guidance on this in the context of the Part IIA regime [19]. It provides a description of the site in terms of:

- source(s) of contamination, including types of contaminant, estimated concentrations and extent;
- the likely migration pathways;
- potential receptors for the contamination.

It is also used to:

- identify key assumptions;
- identify uncertainties;
- provide a basis for determining future data requirements.

The development of a conceptual model is an iterative process; the model should be updated as new data becomes available or as understanding of the system is improved.

Having developed the preliminary site conceptual model, it is important that it is used in the design of the site characterisation programme. Furthermore, this link should be documented so that other parties can understand how the site characterisation programme was developed. Where more than one initial site conceptual model has been developed, site characterisation data should be obtained to test the various models and discriminate between them.

8.3. Site characterisation design

The site characterisation should be designed to be efficient and safe, and to provide data of a quality and quantity suitable to achieve the stated objectives.

A site characterisation is often undertaken in phases. In this way, the conceptual model can be reviewed and refined, and the forward programme modified if appropriate to achieve the objectives of the site characterisation. On a potentially radioactively contaminated site, works will often be carried out in two phases:

- a walkover (non-intrusive) radiological survey;
- an intrusive survey, involving construction, logging and sampling of trial pits and/or boreholes.

The results of the radiological walkover survey are an input to the conceptual model and are used to help design the intrusive investigations. In addition, the design of the intrusive radiological survey should take into account:

- the geology and hydrogeology of the area;
- the degree of uncertainty that is acceptable in the interpretation of the investigation;
- the size and type of samples required;
- waste minimisation;
- health, safety and environmental issues.

8.4. Health and safety

Under the Health and Safety at Work etc. Act 1974, there are a number of regulations that govern the health and safety of workers involved in the characterisation of potentially or actually contaminated land. The regulator is the Health and Safety Executive (HSE). Relevant regulations cover management, working environment, construction and hazards. Site owners and developers should liaise with HSE regarding the applicability of regulations to the planned activities. Guidance on safe working on contaminated sites is given in

.

The Ionising Radiations Regulations 1999 (IRR99) is the principal legislation relating to the protection of workers from ionising radiations. The Approved Code of Practice [21] provides guidance on the legislation. The following are the crucial points relevant to contaminated land:

- **Notification of specified work.** For work involving concentrations and quantities of radionuclides greater than those specified in the regulations, there is a requirement to notify HSE 28 days before starting work. This requirement does not apply to work on nuclear-licensed sites.
- **Prior risk assessment.** Requirement to carry out a "prior risk assessment" before work with ionising radiations. Compliance with this regulation does not remove the need for compliance with the Management of Health and Safety at Work Regulations.
- **Designation of classified persons.** Requires the employer to designate as classified workers any employees who are likely to receive an effective dose in excess of 6mSv per year or an equivalent dose that exceeds three-tenths of any relevant dose limit.
- **Restriction of exposure.** Requirement that doses to employees and others are restricted as far as is reasonably practicable. This embodies the principle of As Low as Reasonably Practicable (ALARP).
- **Dose limitation.** Requires that dose limits for employees and others, as set out in IRR99, are not exceeded.
- **Radiation Protection Advisers.** Requires the appointment of a Radiation Protection Adviser (RPA) to guide the employer on general compliance with the regulations (IRR99).
- **Designation of controlled or supervised areas.** Requires the designation of areas as controlled or supervised depending on the results of the prior risk assessment.

Before starting the site characterisation, it may not be clear whether the nature, quantities and concentrations of radioactivity that will be encountered are such that IRR99 is applicable. However, it is best practice to appoint a Radiation Protection Adviser at the beginning of the project to advise on this and other radiological issues.

On potentially radioactively contaminated sites, information should be obtained from the Radiation Protection Adviser (RPA) on "Hold Points" (that is, radiation levels at which the work would be stopped and working methods and protective equipment would be re-evaluated), radiological monitoring equipment, protective equipment and the like. A suitably qualified and experienced person is required to undertake radiological monitoring on the site. Procedures should be in place for decontamination of personnel and equipment.

8.5. Non-intrusive radiological survey

Ionising radiations (in particular, gamma radiation) can be detected in the field in "real time" using hand-held instruments. In contrast, most chemical contaminants are generally detected at some later date through laboratory measurement (although portable analysers may be used on site). As a consequence, non-intrusive radiation surveys (or "radiological surveys") are a crucial component of any characterisation on a potentially radioactively contaminated site.

Design of the radiological survey

To design a radiological survey, it is important to identify the objective of the work. In most cases, this will consist of one or more of the following:

- to check the validity of the desk study;
- to determine the areal distribution of surface radioactive contamination on the site;
- to determine the fingerprint of radionuclides present on the site (because different radioelements have different mobilities in the sub-surface, the "fingerprint" is only relevant for defining the character of the source area)
- to determine if radionuclides present on a site present a hazard to site personnel.

The radiological survey for a site should be designed by a person competent in the use and limitations of radiological monitoring equipment. This may be the Radiation Protection Advisor for the project. The design of the survey will take into account three main aspects:

- the type of radiological monitoring instrumentation to be used, based upon the expected radionuclides present, the required detection limits and cost/time constraints;
- the survey grid, based on the size of the area to be surveyed and the size of the anomalies expected to be present (including focused surveying of known or suspected problem areas highlighted by the desk study/preliminary conceptual model);
- the most effective method of transporting the radiological monitoring equipment during the survey (single person, ground vehicle or airborne) based upon the selected grid size, the equipment to be used and the availability of equipment.

In addition, the radiological background of the site should be determined so that the local background of natural and artificial radionuclides is established.

Types of field radiological monitoring equipment

The standard monitoring equipment used in the field usually consists of a beta- or gamma-detector of either the gas-filled (for example, Geiger-Muller tubes) or scintillation (for example, sodium iodide detector) types. These monitors are either contamination meters (that measure the relative radioactivity of an area of ground in terms of counts per second) or dose meters (to determine the total external radiation dose that would be received by a person standing on the site). Detectors also are available that can monitor for alpha-emitting contamination and portable gamma-spectrometers can be used to determine the gamma fingerprint of a sample.

The choice of instrumentation

Many different instruments may be used for radioactivity surveys. Each instrument will be designed to monitor for particular radioactivity types or energies. In addition, each instrument will have limitations to its use or may be interfered with by other radiations. Detailed descriptions of some of the advantages and disadvantages of different radioactivity monitors are provided in [22] and [23]. The most appropriate, robust and cost-effective instrument should be selected by an appropriately experienced person.

Which radionuclides can be detected in the field

In general, gamma-emitters and high-energy beta-emitters can be detected using standard walkover survey monitoring equipment. However, alpha-emitters, low-energy gamma-emitters (such as ^{55}Fe) and low-energy beta-emitters (such as ^{3}H) cannot usually be detected.

Alpha radiation cannot be detected effectively using hand-held monitors because most soil in the field is damp and alpha radiation is shielded by a thin layer of water or soil. An estimate of the alpha activity of damp soil can be made by collecting a swab sample (on, for example, filter paper), allowing this to dry and then counting it. Alternatively, soil scrapes may be monitored. In some circumstances, the presence of alpha-emitting radionuclides can be inferred from the presence of gamma-emitting daughters (for example, the distribution of the alpha emitter ^{241}Pu can often be estimated by monitoring the gamma emissions from its daughter ^{241}Am).

Monitoring for low-energy gamma- or beta-emitters cannot be undertaken in the field. Samples should be taken for laboratory analysis if it is suspected that such contaminants are present.

The importance of knowing the radiological signature

Obviously, different radionuclides require different approaches to detect them in the field. It is therefore important to have undertaken a thorough desk study of the site and its immediate surroundings to allow a good estimate of the radionuclide signature to be made, prior to the survey works commencing. The most effective radiological monitoring scheme can then be developed.

Care must be taken when using the concept of a radionuclide “fingerprint”. It is only valid in the source area. Radionuclides will migrate through the sub-surface at rates determined by their chemical characteristics (such as solubility) and their chemical interactions with the soil. The relative activities of radionuclides in the plume are therefore a function of the distance travelled, and the concept of the fingerprint cannot be applied.

Instrument calibration

All radiation monitoring equipment should be routinely calibrated in accordance with manufacturer’s instructions. Before use, the following checks should be carried out:

- a battery check;
- a check of the calibration date;
- a function test, using a source of known activity.

Common mistakes

A common mistake made in interpreting radiological survey data is to assume that if the survey does not highlight any areas of elevated radioactivity, the site is “clean”. However, the shielding afforded by the soil can significantly attenuate all types of radioactivity, including gamma activity. The ability to detect buried radioactivity depends on the type of detector used, the activity of the buried material, the depth of burial and the quantity of the buried material. In many circumstances, gamma-emitting radionuclides buried more than a few tens of centimetres below ground surface will not be detected at surface. As already discussed, pure alpha- and beta-emitting radionuclides are unlikely to be detected if buried.

The radiological survey as input into the design of the intrusive works
One of the major inputs into the design of the intrusive sampling programme on a radioactively contaminated site is the results of the initial radiological survey. This will indicate areas of elevated radioactivity that may require further investigation and sampling to determine quantitatively the concentrations and amount of radioactivity present. Information on the nature of the contaminant distribution (for example, 'as "hotspots", uniformly distributed or associated with certain facilities or activities) will also be obtained. In this way the radiological survey will focus the later stages of work.

8.6. Intrusive investigations

Samples collected during the site characterisation will be of the following types: soils and rocks; surface waters and groundwaters; soil gases. Soil samples are collected manually, by hand-digging or an auger, or mechanically, using an excavator (for trial pits) or drilling rig (for boreholes). Groundwater samples are generally collected from boreholes that are either temporarily or permanently cased, or occasionally from trial pits. Gas samples are generally collected from temporary shallow probes or from boreholes completed as soil gas monitoring points. Details of methods for collecting samples are given in existing guidance (for example, [1] [16].

The SAFEGROUNDS Good Practice Guidance on characterisation of contaminated or potentially contaminated land on nuclear-licensed and defence sites summarises methods of excavating into the sub-surface, with particular reference to the details that make techniques more or less suitable for use on potentially radioactively contaminated sites. Of particular relevance are excavation techniques that minimise the amount of spoil generated and minimise the potential for contamination to be spread around the excavation area. Box 6.9 of the SAFEGROUNDS guidance is reproduced overleaf as Table 7.

There are three broad approaches for soil sampling: (i) collection of samples from predefined depth intervals, (ii) collection from different geological or lithological units or (iii) collection based on visual or monitoring evidence for contamination. Whatever the approach, the samples should be representative of the area from which they were collected, and sufficient material should be collected to enable all required analyses to be undertaken (including sufficient material for repeat analysis, should this be necessary). In general, the largest samples are required for gamma spectrometry analysis: approximately 500–1,000 g of sample is typically sufficient.

8.7. Sampling strategies

Extensive guidance is available on sampling strategies for contaminated land investigations: British Standards Institute's *Investigation of potentially contaminated sites - Code of practice*. [16]; CIRIA's *Remedial treatment for contaminated land*. Volume III: Site investigation and risk assessment [17]; Department of the Environment's (DoE), *Sampling Strategies for Contaminated Land* [24] and, USEPA's *Multi-agency radiation survey and site investigation manual* (MARSSIM) [22], key issues from which are given below.

There are two approaches to soil sampling:

- targeted or judgmental sampling, which focuses on known or suspected sources of contamination such as storage tanks, disposal pits and pipelines;
- non-targeted sampling, which aims to characterise the contamination status of area or volume of ground.

In each case, it is necessary to select the frequency and distribution of sampling points. This can be achieved only by considering the conceptual model and asking questions such as:

- what are the principal pathways for contamination?
- what are the typical sizes and spacings of potential or actual source areas?
- how mobile are the contaminants?
- what are the objectives of the site investigation, and what is the required level of confidence in the results?
- if remediation were required, what averaging volume would be used for waste characterisation? This issue is of greatest importance on sites where contamination is heterogeneously distributed.

Two approaches to designing non-targeted sampling grids are presented in available guidance. The British Standards Institute's *Investigation of potentially contaminated sites-Code of Practice* [16] states that: "*Typical densities of sampling grids can vary from 50m to 100m centres for exploratory investigations, and 20m to 25m centres for main investigations. A greater density of sampling grid could be considered appropriate where heterogeneous contamination is indicated… A high-density sampling grid can also be necessary where a high level of confidence is required for the outcome of a risk assessment.*"

In contrast, the Department of the Environment's (DoE) *Sampling Strategies for Contaminated land* [24] presents a statistical approach in which there are sufficient sampling points to detect a certain size of "hot spot" with a reasonable level of confidence. This approach requires understanding of the probable sizes and spacings of contaminant sources- information that is not always available at the outset of a site investigation. For this reason, the approach to non-targeted sampling presented in British Standards Institute's, *Investigation of potentially contaminated sites - Code of practice* [16] is more frequently used.

The most common non-targeted sampling pattern is the square grid, although the herringbone grid pattern is considered by the British Standards Institutes guidance [16] to be the optimum pattern. Note that, because of underground services and the like at the site, the actual non-targeted sampling grid will probably not conform to the ideal pattern. A judgement then has to be made as to whether deviations from the ideal grid geometry are so great as to render any statistical measures of confidence invalid.

8.8 Radiological monitoring during intrusive works

Radiological monitoring should be undertaken during all intrusive investigations where radioactive contamination may be present. Such monitoring will be for two primary purposes:

- to protect the health and safety of workers;
- to provide data on the distribution of radioactive contamination in the soil (to focus soil sampling and selection of samples for analysis).

Table 7 Techniques for intrusive sampling (reproduced from the Safegrounds Best Practice Guidance on characterisation of contaminated or potentially contaminated land on nuclear-licensed sites and defence sites [1]

Technique	Outline of method	Advantages	Disadvantages
Soil gas probing	Gas sample probe inserted into soil to a depth of <0.5 m	• simple method of obtaining the areal soil gas data • no spoil generated • low potential for contamination to be spread	• only suitable for gas sampling • can only be used at shallow depth
Hand-digging	Use of trowel to collect samples to <0.5 m depth	• samples can be collected from any surface location • base of hole can be monitored during excavation • little equipment is required • low potential for contamination to be spread • low risk of damaging services • cheap	• maximum depth of sampling approx. 0.5 m. • disturbed samples are collected
Hand-augering	Use of hand auger to drill holes in soft materials to a depth of approximately 1 m	• little equipment is required • cheap • samples can be collected in areas with poor access	• maximum depth of sampling 1–2 m • samples are significantly disturbed and there is a high potential for cross-contamination of layers • only appropriate for fine-grained, soft sediments
Trial pitting	Use of tracked or wheeled excavator to dig trial pit to <6 m depth	• large volume of soil exposed – sampling and logging more representative • observations of base of trial pit can be used to identify potential hazards • base of excavation may be monitored for services and contamination as trial pit progresses	• large quantities of potentially contaminated waste materials brought to ground surface • medium risk of damaging services (unless banksman identifies marker tape and the like.) • maximum depth 6 m – note that the trial hole will often collapse when groundwater is encountered
Borehole drilling	Cable percussive drilling in soils/weak rocks	• suitable for a wide range of materials • suitable for in-situ geotechnical testing and geotechnical sampling • good definition of depth of materials • little or no use of drilling fluid • suitable for the installation of permanent groundwater or gas monitoring installations • possible to use low-headroom rigs for sampling in difficult areas	• drilling process produces relatively large quantities of spoil (although less than trial-pitting) • driller's mate is closely involved with the drilling process and has a relatively high potential of becoming contaminated • relatively slow • maximum depth tens of metres depending on material

Technique	Outline of method	Advantages	Disadvantages
Borehole drilling (continued)	Solid stem rotary augering in soils/ weak rocks	• relatively fast • little or no drilling fluids required • suitable for installing permanent groundwater or gas monitoring installations • can undertake inclined drilling for sampling under buildings and the like	• high potential for cross-contamination of samples • depth resolution poor • not appropriate for coarse, gravelly materials
	Hollow stem rotary augering in soils/weak rocks	• relatively fast • good quality samples • good depth definition • suitable for installing permanent groundwater or gas monitoring installations • can undertake inclined drilling for sampling under buildings and the like	• not appropriate for coarse gravelly materials
	Rotary drilling in rock (truck- or mini-rig mounted)	• rapid drilling possible • can be used to drill through overburden using rotary-percussive drilling • maximum depth hundreds of metres • good-quality core and samples • suitable for installing permanent groundwater or gas monitoring installations	• expensive • drilling fluids may contaminate sampled and surrounding rock • difficult to control and dispose of drilling fluids and cuttings • difficult to monitor drilling cuttings • truck-mounted rigs not suitable in restricted space areas
	Windows sampling	• small quantities of waste produced • core can be produced in clear plastic sleeves • simple to monitor cores to select samples and for health and safety purposes • relatively quick • cheap • possible to use in restricted space areas	• maximum depth usually less than 5 m • samples are usually compacted • small quantities of sample are recovered • samples are not suitable for many geotechnical tests • difficult to identify water strikes • not very reliable in granular soils

8.9. Background measurements

Many radionuclides are common in the environment, either because they are naturally occurring (such as K-40 and the U- and Th-series radionuclides) or because they are a consequence of fallout from nuclear weapons testing or Chernobyl (for example, tritium and Cs-137). It is important to establish the levels of "background" radioactivity at the site for two reasons:

- a knowledge of background level of radioactivity is needed to inform decisions on management options;
- the determination of whether a substance is exempt from consideration as a radioactive material under the SoLA Exemption Order made under RSA 93 is related to the background activity for the area.

Background levels of radioactivity will vary (i) from site to site and (ii) spatially within a site. Concentrations of naturally occurring radionuclides will be strongly influenced by the composition of the rocks and soils, and by the extent of near-surface weathering effects. Anthropogenic radionuclides derived from global fallout are (with the exception of tritium) unlikely to penetrate significantly below surface soils; it would therefore be inappropriate to use the background levels of such radionuclides in surface soils to derive a background for deeper soils and rocks.

To determine background levels of radioactivity at a site, it is necessary to characterise an area that has similar rock and soil compositions to the site under investigation, and to evaluate any depth-dependent changes in the background activity of naturally occurring and fallout-derived radionuclides.

8.10. Waste management

Liquid and solid wastes will probably be generated during site characterisation.

Typical solid wastes may include:

- solid wastes from initial site clearance activities;
- spoil from boreholes or trial pits;
- used personal protective equipment and respiratory protective equipment;
- disposable items used during sample collection, preparation and packaging;
- waste from the site accommodation and hygiene facilities;
- residues from samples sent for laboratory analysis.

Typical liquid wastes may include:

- water produced from wash-down facilities (that is, water used for cleaning and decontaminating plant and sampling equipment);
- water produced from operations in the hygiene and change facilities;
- water produced from abstraction of groundwater from trial pits, trenches and boreholes on the site;
- residues from samples sent for laboratory analysis.

Wastes will be disposed of using various routes at different phases of site investigation depending on the levels of activity and the disposal routes available. Bear in mind that securing authorised disposal routes will require time and resources. Consequently, it is best practice to minimise the quantities of waste generated during the works by selecting appropriate characterisation techniques.

It is not possible to cover all circumstances here; case-by-case judgements will be needed. Small samples sent to analytical laboratories will often be stored for further analysis (as radioactive material) or disposed of as radioactive waste under the RSA 93 authorisation for that laboratory.

Core samples are normally assessed on site against the applicable Exemption Order and then:

- if clean, returned to the ground as backfill;
- disposed of with other exempt waste from remediation to appropriate sites;
- transferred to Drigg as LLW with other LLW from remediation.

8.11. Decontamination and radiological clearance of equipment

All intrusive investigation equipment should be monitored for radioactive contamination between sampling locations. If any contamination is discovered, the equipment should be decontaminated. Decontamination may involve washing or, in some cases, dry swabbing. Regardless of whether contamination is detected or not, it is good practice to clean equipment between sampling locations to minimise the potential for cross-contamination.

On completion of the site works in a potentially radioactively contaminated area, it is good practice to have all site investigation equipment radiologically monitored and a radiological clearance certificate issued. If work is taking place in a radiologically designated area, this is a necessity.

8.12. Analytical techniques

Analytical techniques for radioactivity are divided into two main types: screening techniques and detailed analysis.

Laboratory screening techniques, for example:

- gross alpha/beta;
- gamma spectrometry.

Specific radionuclide analysis, for example:

- alpha spectrometry to determine activities of uranium and plutonium isotopes;
- scintillation counting for tritium;
- Sr-90 analysis;
- C-14 analysis.

The two principal analytical techniques used to detect radioactivity in soils and waters are gross alpha/beta analysis and gamma spectrometry. These techniques are discussed further below.

Gross alpha and gross beta measurements
In principle, a gross alpha and gross beta measurement will be sufficient to characterise the total radioactivity of the sample. This is the case for analysis of water samples, where detection to less than 0.1 Bql^{-1} can be achieved. However, gross alpha/beta analysis of soil samples should be considered as a screening technique that can be used to distinguish between uncontaminated samples and those contaminated to a few Bq/g or more because:

- the size of soil sample required for analysis is very small (<1g) and sub-sampling errors (arising from sample heterogeneity) may be significant;

- the typical sample preparation technique involves using only the fine-grained (<200 μm) portion of the soil. This can introduce a systematic bias in the result, because any radioactive contamination tends to be associated with the fine fraction;
- gross beta analysis does not detect very weak beta–emitters such as tritium and C-14. If these isotopes may be present, additional isotope-specific analysis is required.

A more accurate measurement of gross alpha/beta activity in soil can be obtained if a 100g-sized sample of soil is homogenised and crushed so that there is no size separation prior to analysis.

Direct counting can be improved by dissolution of the bulk sample in HNO_3/HF, followed by evaporation to dryness and re-dissolution in dilute nitric acid. An aliquot may then be counted by a liquid scintillation counter or a thin source prepared upon a planchet. This approach avoids problems of sample heterogeneity and self-shielding.

Gamma spectrometry
Gamma spectrometry detects gamma radiation, which is produced during the decay of most radionuclides. However, there are some potential radioactive contaminants, such as ^{90}Sr, which do not produce gamma radiation on decay and whose presence cannot be inferred from short-lived gamma-emitting daughter radionuclides.

In soil samples, gamma spectrometry is ideal as a complementary screening measurement to gross alpha/beta. The required sample size is in the range 100g to several kilograms. This is significantly larger than that required for gross alpha/beta analysis; hence sub-sampling errors will be smaller and results are likely to be more representative of in-situ conditions. In particular, activities of common man-made radionuclides, such as Cs-137 and Co-60, and of the natural series decay chains (headed by U-235, U-238 and Th-232) can be measured or inferred.

However, because not all radionuclides will be detected using gamma spectrometry, the technique should not be used in isolation unless the radionuclide fingerprint of the contaminated site is well understood.

8.13 Reporting and interpretation of data from site characterisations

It is standard practice to report the site characterisation work. The following aspects should be considered for inclusion in the report:

- the objectives of the study;
- all relevant information collected during the desk study and walkover, plus a description of the initial conceptual model of the site;
- the design of the site characterisation and the reasons for the design;
- the methodologies employed, both during site characterisation and for analysis;
- the results of any radiological surveys undertaken;
- the number of samples collected, a plan of sampling locations, sample sizes and reasons for collection;
- logs of any boreholes or trial pits constructed (including field-monitoring results);
- the analytical results;
- Quality Assurance arrangements.

The results then need to be interpreted. The form of this interpretation depends on the objectives for the work. The site characterisation studies will normally be used to refine the conceptual model; this is often an iterative process. The following aspects may be appropriate for an interpretative report:

- contoured plots showing the areas of contamination (these may need to be provided separately for surface and sub-surface contamination and take account of drains and sumps);
- a revised conceptual model, with quantitative information on:
  - contaminant concentrations;
  - direct doses;
  - contaminant pathways;
  - receptors;
- volume estimates for contaminated soil that may need to be removed in the event of remediation, broken down by probable disposal route;
- key assumptions and uncertainties;
- recommendations for further characterisation if necessary.

For many site characterisation programmes, input, storage and presentation of data digitally can be an advantage. In particular, digital data can be transferred between interested parties easily and can be organised, interpreted and spatially plotted using packages such as geographical information systems.

9. OPTION STUDIES, PLANNING AND COMPLETION

9.1. Planning

The remediation strategy for contaminated land is normally defined and developed through a collaborative process between the owners/developers of the site and the local and national regulatory authorities concerned with planning, health and safety, environmental impact, waste management and disposal. The requirements for remediation of the site depend on projected future uses as well as the scale and nature of the contamination. For example, a development resulting in free access to the site for any purpose, including recreation and food production (gardens or allotments) may require a different level of remediation than that for light industry where the contaminated soil will be covered with concrete or tarmac. The appropriate degree of remediation may also differ depending on whether the site is to remain in the hands of the liability owner for the indefinite future.

The initial planning phase for remedial activity will therefore involve establishing the required end-points for the remediation activity and also the methodologies required to demonstrate that these end-points are appropriate and have been achieved. This phase requires the close co-operation of all the relevant interested parties. Setting the remedial targets, and the methodologies available to do this, are considered in sections 6 and 7.

The planning phase should also address the health and safety, environmental impact and waste management issues associated with the remediation process itself (as well as the end-point of the process). For example:

- have the potential radiological exposures to the workforce been minimised (by using containment or protective equipment, if necessary)?
- are the wastes generated being adequately segregated into appropriate waste streams?
- are the wastes being generated in a form suitable for disposal, or is additional processing/treatment required (for example, mixed organic and radioactive wastes are not acceptable at Drigg)?
- what waste monitoring/assay procedures will be used and how will these be calibrated?
- is containment of the process or emissions appropriate?
- will dust or odour generation be an issue?
- has the potential for release of contaminant material off-site during the remediation activity been assessed (for example, via contaminated soil on lorry wheels)?

- is external environmental monitoring required?
- is noise an issue?
- site security (prevention of inadvertent or unauthorised entry).

The types of remediation techniques that can be employed are discussed in Annex 1.

In general, the preliminary preparation work normally includes the following items :

Design and documentation approval (Quality Assurance):

- remediation plan;
- safety case(s);
- method statements;
- environmental impact assessment;
- appropriate regulatory permits/licences to undertake the work.

Preliminary surveys (baseline surveys) that are non-intrusive (for the site and the appropriate local area):

- baseline site environmental conditions;
- health physics/radiation monitoring surveys;
- surveys of existing services, boreholes and structural features;
- a "before" remediation topographic survey;
- baseline noise surveys undertaken at suitable times during both day and night;
- baseline environmental monitoring surveys;
- baseline condition of existing site security features;
- baseline photographic/video surveys to give "before" remediation status.

Determination of background:

- take a suitable and sufficient number of samples/analysis to determine reliable statistics for the determinant.;
- take account of published background concentration information;
- take account of the limits of detection and analytical accuracy statistics of the methods used;
- determine sample means and deviations and hence derive population mean confidence limits;
- report background determinations with the full statistical caveats and features that apply to those statistics.

Site preparation:

- setting up site security and site access control;
- setting up communications;
- setting up arrangements/co-ordination with emergency services;
- ground clearance- clearing trees and ground vegetation;
- arrangements for protection of boundary hedges and trees where practicable and appropriate;
- completion of baseline and preparatory site surveys;
- disconnection and making safe termination of existing services, including arrangements for searching for such services;
- establishment of site services;
- uprating of access roads if required;
- preparation of areas for:
  - storage and packaging facility;
  - site accommodation;

- car park;
- storage area for containers;
- equipment unloading area;
- wheel wash and vehicle decontamination centre.

9.2. Completion

The main requirement for completion of the remediation project is to demonstrate that the remedial end-points have been achieved. This will require remediation surveys (Section 8) and also possibly monitoring for a period after remediation.

Once demonstration of the remediation has been established and accepted, then the site can be cleared and reinstated through backfilling of any pits and landscaping to ensure that the site is left in a safe and tidy state.

Records should be kept showing what was done on the site (and where), what kind, and quantity, of waste types were removed and where these were disposed. Records should also include, if appropriate, details of post-remediation monitoring programmes.

In cases where radioactively contaminated material is left on site after remediation, Agency officers should consider the appropriateness of recommending to local planning authorities that conditions are attached to planning permissions, or that records are kept so that the contamination is taken into account when considering future changes of use.

10. REFERENCES

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11. GLOSSARY

Becquerel (Bq)

The international (SI) unit for the number of nuclear disintegrations occurring per unit time in a quantity of radioactive material. Replaced the Curie (Ci) – 1 Bq = 2.7×10^{-11} Ci.
1 Bq = 1 radioactive disintegration per second.

Because this is an extremely small unit, levels of activity expressed in Bq are often prefixed with Mega (10^6Bq – MBq), Giga (10^9Bq – GBq) and Tera (10^{12}Bq – TBq).

Committed effective dose

The sum of the products of the committed organ or tissue-equivalent doses and the appropriate organ or tissue weighting factors integrated over 50 years for adults and 70 for children.

Critical group
The exposed group receiving the highest dose from the given source.

Effective dose
The summation of the equivalent doses to the individual tissues of the body, weighted by the appropriate tissue-weighting factor.

Exposed group
For a given sources any group of members of the public within which the exposure to radiation is reasonably homogenous; where the exposure is not certain to occur, the term potentially exposed group is used.

Daughter products/Decay product
A nuclide or radionuclide produced by decay. A decay product may be formed directly from a radionuclide or as a result of a series of successive decays through several radionuclides.

Intermediate-level waste
Wastes with radioactivity levels exceeding the upper boundaries for low level wastes, but which do not require heating to be taken into account in the design of storage or disposal facilities.

Low-level waste
Wastes containing radioactive materials other than those acceptable for disposal with ordinary refuse, but not exceeding 4GBq/t alpha or 12 GBq/t beta/gamma activity (for example, wastes which, under existing authorisations, can be accepted by BNFL at Drigg)

Radioelement

Radionuclide
A type of atomic nucleus that is unstable and that may undergo spontaneous decay to another atom by emission of ionising radiation (usually alpha, beta, or gamma).

Sievert (Sv)
The international (SI) unit of effective dose, obtained by weighting the equivalent dose in each tissue in the body with ICRP-recommended tissue-weighting factors, and summing over all tissues. Because the sievert is a large unit, effective dose is commonly expressed in millisieverts (mSv) – that is, one thousandth of one sievert, and microsieverts (µSv) – that is, one thousandth of one millisievert. The average annual radiation dose received by members of the public in the UK is 2.6mSv.

ANNEX 1

RELEVANT REMEDIATION TECHNOLOGIES

In selecting any single or combination of technologies to remediate a contaminated site, a number of factors are important and have to be considered. These include:

- the nature of the contaminants, including their half-lives;
- the associated contaminants;
- the distribution of the contaminants on and below the surface;
- the nature of the soil and underlying geology/hydrogeology;
- the scale of the contaminated zone;
- the level of risk posed to the local population, workers and the environment;
- the availability of disposal routes, segregation and minimisation of wastes;
- the infrastructure on the site;
- the lifetime of the site;
- the endpoint(s) of the site;
- the state of development of available technologies;
- the cost and timescale.

In this section, the available technologies are briefly described. These include the following approaches:

Excavation and disposal:
- removal of contaminated material from the site and disposal elsewhere.

In-situ
- electro-remediation
- soil washing/flushing
- immobilisation (vitrification, solidification, stabilisation)
- phytoremediation.

Retrieval and separation technologies:
- surface soil removal
- surface turf removal.

Ex-situ:
- detector-based segregation
- physical soil washing
- chemical treatment
- thermal treatment.

Containment:
- curtain walls
- capping.

Information on remediation techniques for chemically contaminated land has been prepared by CIRIA [i]. The Agency has compiled information relating to techniques for the remediation of chemically and radioactively contaminated land [ii] Further guidance on remediation will be produced through the SAFEGROUNDS learning network.

A.1.1 Excavation and disposal

The most common approach to site remediation worldwide has been to excavate affected areas and to dispose of the contaminated soil in a licensed facility. In the absence of approved disposal routes, it may be appropriate to store the material in approved containers and facilities as an interim measure. In considering this option, developers need to be aware of the limited capacity of the Drigg disposal site for LLW disposal.

All waste generated during the remediation project must be effectively segregated into the various waste streams described in Section 4; non-active (outside the scope of RSA 93), exempt and LLW, using the best practicable means available. This is also required to ensure compliance with relevant legislation as discussed in section 4. To achieve this, some kind of field measurement system is required that can be calibrated to give sufficiently accurate measurements of specific activity of the various radionuclides in the waste material being removed and to demonstrate compliance with disposal authorisations and requirements. The field measurement system might need to be supplemented with additional sub-sampling and detailed analysis in the laboratory depending on the nature of the contaminant.

Some aspects of this approach are set out below:

Survey

The area is surveyed using the procedures described in section 8 on baseline surveys (external γ and the like.).

Identification and remediation of "hot spots"

Any hot spots identified during the surveys should be marked and investigated before excavating of the remainder of the surveyed area. It may be appropriate to use hand-held monitors and hand tools to examine and segregate the "hot spots" of contamination.

Excavation of remaining area to depth of g survey (typically 300mm)

Evacuation methods employed will depend on the scale of contamination. For larger sites the previously surveyed area may be excavated to the depth of the γ survey using an excavator. Material would then be placed into stockpiles in previously defined areas prior to waste sentencing. All stockpiles of will be clearly segregated to keep sorted material and un-processed earth separate.

Wind fences and damping down may be required to reduce dust generation and migration.

Any redundant contaminated drains discovered on the site are excavated and removed after assessment. The excavations should be accompanied by health physics surveys of the drains and associated soakaways.

The above sequence of "Survey – Remediation of "hot spots" – Excavation in layers" can be repeated until the ground level is found to be consistent with the agreed remediation standard. As noted before, the depth of excavation of each level will be to the depth of the γ survey.

Containment

Depending on the nature and concentration of the contaminated material, it may be necessary to conduct the excavation inside some type of containment (tent or temporary building) with the ventilation extract from the containment filtered to remove potential airborne contaminants. It may be necessary to obtain a discharge authorisation for the discharge of radioactive wastes from the Agency.

Waste disposal
The excavated material is assayed and characterised before being disposed of to an appropriate waste disposal route for the category of waste. Methodologies will be required for handling large items and for handling specific containers and individually segregated wastes.

Compliance with non-radioactive waste disposal requirements and duty of care will also be necessary. Where clean soil has been excavated, and characterised as such, it can be used to backfill the excavation as appropriate. Otherwise clean imported fill will be required.

Management systems
Operators should have in place appropriate quality assurance and management systems for waste segregation, classification, monitoring and sentencing. The use of such systems may be considered by the Agency in determining whether "best practicable means" are being applied to minimise impact of waste disposals.

A.1.2 In-situ techniques

Large-scale earth moving can cause disruptions on sites and may not be possible close to existing plant or buildings. The potential advantage of in-situ remediation technologies is that they could eliminate the need to excavate and transport large volumes of contaminated soil; a process that is capable of spreading contamination unless strictly controlled. The main in-situ techniques that may be relevant for treating contaminated soils are: electro-remediation, vitrification, bio-remediation and vapour extraction.

Vacuum extraction and bio-remediation are techniques commonly used for treating organic chemically contaminated soils. Thus their main application for radioactively contaminated soils is in removing non-radioactive organic contaminants. This may reduce the mobility of the radionuclides (and hence reduce the radiological impact) or facilitate their processing by other techniques. Biotechnology is being developed as a treatment for metal contamination of aqueous streams and also for removing radioactivity from contaminated surfaces. Indeed, it has been used for selectively leaching radioactive elements, such as uranium, from ores and the like., in mining. So far, however, it has not been applied full-scale to radioactively contaminated soils.

Electro-remediation

Electro-remediation or electrokinetic soil processing is an in-situ technique that uses an electric current passed between arrays of anodes and cathodes implanted in the ground to decontaminate soils and slurries that contain radionuclides, heavy metals, certain organic compounds or mixed organic and inorganic wastes. The passing electric current has several effects. It induces ionic migration and electro-osmotic advection as well as electrolysis reactions at the electrodes. An acid is produced in the anode region that sweeps across the soil and desorbs contaminants from the soil particles. Electromigration of different species is initiated towards their respective electrodes. Mobile ions are driven towards the electrodes where they are removed from the ground by circulation of electrolyte around the electrode. This produces a liquid waste stream containing the contaminants, which can then be treated by techniques such as standard or electrochemical ion-exchange.

The relatively simple equipment needed consists mainly of an array of electrodes, typically spaced at 6-10 m intervals, a network of pipes circulating electrolyte to and from the individual electrodes, an electricity supply unit (either from the local supply or by generator) and the effluent treatment and electrolyte conditioning plant. Electroremediation is an in-situ process, which once set up, requires minimal supervision. The electrolyte preparation and treatment units can be mounted in containers, which can easily be transported when remediation is finished.

The technique has several potential applications beyond enhancing chemical migration that may be of benefit in site remediation. It can be employed in implementing electrokinetic flow barriers; diverting contaminant plumes; detecting leaks and injecting chemicals, grouts, micro-organisms and nutrients into subsurface deposits.

In-situ soil flushing

Soil washing is a technique usually carried out in process plant once the soil has been excavated from the site. However, in certain conditions soil washing can be carried out in the ground. A solvent is injected into the soil, passed through the ground and extracted at a predetermined boundary. The technique usually requires the installation of some form of in-situ containment to prevent the contaminants being diluted over the site. In-situ washing is operated in conjunction with an ex-situ liquor-treatment facility. The environmental impacts and regulatory requirements of in-situ treatment would need to be carefully considered.

In-situ immobilisation

In-situ grout injection is used to contain waste material in a solid monolith by mixing it with cement grout, thereby increasing the waste's physical stability and compressive strength, decreasing water intrusion to the waste and decreasing the leachability of the waste. Soil characteristics are important in influencing whether effective containment will be achieved. These include void volume, soil pore size and permeability. Grout can be injected through a pipe drilled or hammered into the ground. A variant is to use a pipe with a mixing apparatus that rotates as a grout is injected. This apparatus can use drill bits such as giant augers up to a 2 m in diameter. With this latter type of equipment, monoliths are formed by overlapping the grouted columns. Many types of grout are potentially usable with the most common being cement-based for example, ordinary Portland cement, fly ash and blast furnace slag.

In-situ vitrification is a process of converting materials into glass or a vitreous-type material at high temperatures. In some respects It resembles the joule ceramic melter (JCM) approach for vitrifying high-level waste, but where the soil acts as the feedstock for vitrification and the unmelted surrounding soil acts as the insulating cavity. As a process, it is very energy-intensive and costly to deploy. Its processing rate is low, but it does produce a wasteform, that has high density, durability and leach resistance. Care has to be taken to remove objects that could disintegrate violently upon intense heating. The vitrification process destroys organics present and is capable of solidifying a wide variety of wastes. As a consequence, the process has mainly been used for vitrifying highly active "hot spots" and debris pits. Care would need to be taken to minimise the impact of inadvertent gaseous discharges – these may contain low volatility radionuclides such as Cs-137.

A.1.3 Retrieval and separation technologies

Removal of surface soil

Dependent on the soil and ground characteristics, much of the radioactivity is frequently contained in the top 5-10 cm layer of soil, particularly so for atmospheric "fall-out" type events. Thus a large reduction in contamination can be achieved by stripping off this top layer of soil using earth-moving equipment. Complete removal of the contaminated layer of surface soil is without doubt the most effective and most publicly acceptable means of decontamination. However, it does not result in a reduction in volume.

A variety of commonly available earth-moving equipment, such as graders, bulldozers, front-end loaders, excavators, scrapers and even road planers, can be effective in removing layers of contaminated soil. The depth of the soil layer removed using such machines is at least 5 cm, which may be excessive in certain circumstances. The effectiveness of the treatment depends greatly on the type of terrain and soil. This type of decontamination is most effective in flat, relatively large areas having fine-grained, compacted earth. to remove all of the contamination, the layer removed should be slightly greater than the irregularities in the surface. Field studies carried out in the USA, Russia and Ukraine have produced removal efficiencies of 80-100 per cent with all the above equipment. During these operations it is very important to minimise resuspension, to reduce the potential spread of contamination, and inhalation of dust by operators. This can be achieved simply by using water sprays, but soil stabilisers, such as various polymer solutions, are effective in fixing the contamination and can increase the efficiency of the removal process.

Although it can be highly effective, removal of surface soil is expensive, time consuming and results in a disposal problem. The cost of removing and transporting the upper 5 cm of soil is estimated to be £10,000-20,000 per hectare. This soil can then be sent for further treatment or disposed of directly. The disposal options are to remove the soil completely from the site to a waste repository such as Drigg, or if the activity levels are sufficiently low to a licensed landfill capable of taking special waste. Alternatively, the waste could be piled up in-situ in self-shielding stabilised piles. The area occupied by these in-situ disposal sites would be 5-10 per cent of the decontaminated area. Such on-site disposal requires authorisation from the Agency. Resuspension and erosion of these disposal areas also need to be considered.

The removal of the surface layer can also be extremely damaging to the fertility of the soil, and if all vegetation is removed a barren landscape will be produced that is highly susceptible to soil erosion through runoff and aerial resuspension. Removal leaving some vegetation is preferable, but is difficult to achieve. At present there is no suitable equipment, and in any case such treatment would be less effective both in removing contamination and reducing doses. To help this situation and aid revegetation, grass seed, fertilisers, organic matter or clean soil could be applied to the treated areas.

A new technique, currently being developed at the Institut de Protection et de Sureté Nucléaire (IPSN) in France, involves the application of an organic polymer gel that traps the top layer of soil particles. This can then be removed by mechanical brushing. To date only laboratory trials have been carried out, but the most efficient of the polymers tested removed 80 per cent of the Cs and 65 per cent of the Sr.

Removal of surface turf

On grassed areas, the top 5 cm of the surface can be removed using a turf-cutting machine. This technique is very effective and most easily used on moist turf. However, the volumes of waste produced are quite large, approximately 500 m^3 per hectare.

Another technique, the Decontaminating Vegetal Network (DVN) has been developed at IPSN in France. This aims to reduce the amount of soil removed and hence the amount of waste generated. The technique involves sowing a special variety of fast-growing grass on the contaminated soil to produce turf with a root mat layer in the top soil. This may then be removed, together with a soil layer less than 2 cm thick, using a turf harvester. The grass seeds and nutrient solution can be applied from a truck or from a helicopter, which allows very rapid application. One proposal for dealing with the waste involves putting the turf in plastic-lined trenches and covering it with water. As the grass and its roots biodegrade, the radioactivity passes into the water, which can then be treated by normal ion exchange techniques to reduce the volume of waste. This type of disposal technique requires an authorisation from the Agency.

A.1.4 Ex-situ technologies (separation techniques and/or volume reduction)

For any ex-situ technology the first task is to clear the ground of vegetation and then to excavate the soil. The area and depth of soil removed should be determined from the site investigation phase.

Ex-situ technologies can be split roughly into three categories: physical treatment, chemical treatment and thermal treatment, although there is considerable overlap between physical and chemical methods.

Physical treatment – detector-based segregation

The most commonly used physical process is detector-based segregation where the radioactivity is detected and the contaminated soil removed. There are a number of automated versions of this, where material is placed on a conveyor belt and passed under a detector. Division gates then segregate contaminated from uncontaminated material based on the resulting activity readings.

Physical treatment – particle separation

Soil is heterogenous mixture of components in varying proportions. Physical treatment processes depend upon the contamination or activity within the soil being associated with a particular minority component of the soil, which can be separated from the bulk on the basis of a property difference. Common exploitable differences between contaminated and clean particles include size, specific gravity, particle shape, magnetic properties, friability, and wettability. Such techniques have proved to be particularly applicable for actinides, such as Pu, and fuel fragments, where density differences can be utilised.

Cs-137 or Sr-90 may be specifically absorbed onto peaty matter or iron oxides in the soil, both of which have a different specific gravity than the majority of the soil particles. These radionuclides could therefore potentially be isolated by specific gravity separation.

Cs-137 is strongly absorbed onto clays, which are usually present in soil as the smallest size fraction. Physical separation by a combination of disaggregation, sieving and classification (via settling velocity separation, for example) can effectively remove the clay fraction from a soil. Where size separation techniques have been used to treat non-radioactive contaminated soil contamination, removal of up to 96 per cent has been achieved and given volume reduction factors of 3-20.

High-gradient magnetic separation has been used in the USA for separating plutonium contamination.

Soil washing (leaching or chemical treatment)

The main treatment in this category is soil washing. This can either be physical particle separation or leaching or both. In its simplest form this involves contacting the soil with a solvent solution, so that any soluble contamination passes into the leachate phase. The soil and its leachate are then separated. The "clean" soil can be returned to the area of excavation and the leachate is treated to concentrate the contaminants in a solid form by processes such as precipitation, adsorption and ion exchange. In-soil washing using water is rarely enough to dissolve the contaminants. Solvents are used, including complexing agents, acids, alkalis or other extraction liquors. The plants used in soil washing generally use standard mineral processing equipment.

Thermal techniques

Incineration and vitrification are the two main thermal techniques used for treating contaminated soils. Neither of these leaves clean soil as a product for reuse. Incineration will reduce the volume of waste for disposal, particularly with peaty soils. However, incineration plus treatment and storage of the ash is very expensive.

Ex-situ vitrification converts the radioactive contaminants into an immobile form, which then requires storage and ultimately disposal. Again, this process is energy-intensive, expensive and designed for use with highly contaminated soils that need to be stabilised for a geologically significant period.

In both cases, the potential for the release of radioactive contaminants to atmosphere needs to be considered. Authorisation for the process under RSA 93 may be necessary.

Phytoremediation

Phytoremediation is the accumulation of soil contaminants in plant biomass. This is a relatively slow and low-cost methodology, and is most effective where contamination is widespread but confined to the upper soil layers within the plant-root zone. The principle is to concentrate the contaminants in the above-ground parts of the plant, which can be readily harvested. Some additional waste treatment or processing, such as composting, will be required before the harvested material is suitable for disposal. Phytoremediation may also be used as a means of stabilising contaminants.

A.1.5 Containment systems

A number of techniques exist with the aim of containing the contamination, so that the release (leach) rates are sufficiently low and the risks posed are acceptable. Containment can be an attractive option in cases where the contamination is due to relatively short-lived radionuclides. Containment systems can also have a strong effect on the groundwater flow regime and may be used specifically for that purpose.

Vertical in-ground barriers (curtain walls)

Physical containment can also be achieved by constructing curtain walls around the region of contaminated ground. This approach is preferably utilised where there is an effectively impermeable confining layer, such as clay, bed rock or a horizontal in-ground barrier, without significant fracturing underlying the site, into which the wall can be keyed. In some cases, the layer below the site may be grouted up to effect a seal using horizontal walls. However, this technology has not been widely applied and is generally less suitable where the underlying geologies are both permeable or fractured.

Curtain walls can be formed by conventional civil engineering technology. The forms include slurry walls, sheet-piled walls of various designs and overlapping grouted boreholes. As a containment technology, it is not ideally suited to treating very large areas of contaminated ground. And there are practical limitations on the depth to which it is economic to use it. There are also uncertainties over the duration for which the containment can be maintained - tens of years being most likely. This limits the benefit of containment where longer-lived radionuclide are significant. However, it could be usefully employed as an interim measure until longer-term solutions are identified.

Innovative forms of physical containment

Some innovative forms of physical containment are also under development. These include bioclogging and chemical precipitation. These have the objective of sealing cracks, pores and other potential leak paths in-situ.

No containment system is absolutely effective, but they can usually restrict contaminant migration rates to acceptably low levels. In some cases the physical barrier approach can be allied with chemical or biological fixation to restrict migration further. This can be achieved by incorporating ion exchange or other sorbing materials, and the like., into grouts during curtain wall construction or by injecting biological fixing, chemical precipitation or redox manipulation solutions. Such approaches generally require tailoring to specific radionuclides.

Capping

This form of physical containment is usually applied where the major risk from the contaminants arises from intrusion or inhalation rather than migration in groundwater. It reduces airborne contamination and migration by this route and can also be used to reduce the direct external dose from the contamination. Plus it restricts migration of soluble radionuclides by minimising rainwater infiltration.

A.1.6 References

[i] *Remedial processes for contaminated land: principles ad practice*. C549. CIRIA 2001.

[ii] *Technical support materials for the regulation of radioactively contaminated land*. Environment Agency 1999. R&D Technical Report P307.